The Mars Relay

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Abstract

The UHF Mars Relay onboard the orbiting Mars Global Surveyor spacecraft provides data relay capability for landed systems on Mars. The Relay was employed to provide exclusive data return for the New Millennium Deep Space Two Mars Microprobes and backup data return for the Mars Polar Lander near the South Pole of Mars during the period of landed operations beginning 2000-12-03. Although the Mars Relay was active at the time of expected landed operations, no data from either surface mission were return through the Relay due to failure of both landed systems. However, the 1-watt signal, from the Relay in low circular polar orbit about Mars, was exploited, using the SRI 46-meter Antenna at Stanford University, to probe the Martian atmosphere and ionosphere at UHF frequencies. Internal telemetry and independent Earth-based observations on the Mars Relay UHF signals confirm the relay's functionality. The Mars Relay continues to represent a telecommunications resource for data return from Mars.

1. Introduction

Spacecraft telecommunication equipment for Deep Space Missions is often highly constrained by spacecraft electrical power limitations, equipment mass, antenna pointing requirements, and data rate requirements, among others. Exploiting an existing orbiting spacecraft for data return to Earth from the surface (or near-surface) of a planet can greatly relieve many of the engineering constraints on the telecommunication system used on a landed vehicle. For example, the signal level improvement of communicating to an orbiting spacecraft only 1000 km distant versus communicating directly to Earth at 100 million km distant is of order 100 dB (decibels). With the greatly enhanced communication margins of relay through an orbiting spacecraft, many benefits can be realized, such as, reductions in communication power and transmitter size, increased data rates, operational simplicity, and with the use of omni-directional antennas, the elimination of complex steerable antennae. The Mars Relay (MR) on the Mars Global Surveyor (MGS) spacecraft achieves these benefits at Mars.

The Mars Relay was designed and built by the Centre National d'Etudes Spatiales (CNES), the French Space Agency, and provided to the NASA Mars Global Surveyor (MGS) Program. Very similar relay units were built and provided by CNES for the NASA Mars Observer Mission and the Russian Mars 96 Mission, to support data return, originally from atmospheric balloons, and later, from surface stations and penetrators. Both the Mars Observer and Mars 96 Missions failed prior to arrival at Mars. However, the Mars Global Surveyor spacecraft, with the Mars Relay on board, successfully achieved orbit at Mars on September 12, 1997 after a ten-month cruise from Earth. Following an extended period of aerobraking, complicated by structural problems in one spacecraft solar array, MGS arrived in a low circular, polar orbit to begin mapping operations approximately 400 km above the Martian surface. Details of the MGS spacecraft and mission can be found in [*Albee*, 1998].

2. Instrument Description

The Mars Relay (MR) on MGS is an ultra-high frequency (UHF) telecommunications relay system, capable of one-way data communication [see *Ribes*, 1995]. The Relay broadcasts a beacon to establish communications with a designated surface vehicle. Data from the surface vehicle is then received at the MR and forwarded to the Mars Obiter Camera (MOC) on MGS for data buffering. The MR lacks any internal data buffering or storage capability. Therefore, the large memory in the MOC is exploited for the purpose of relay data storage. The MOC returns the relay data to Earth via the MOC science packets, similar to standard MOC science data. Coordinated interaction with the MOC is required for data return, which adds some complexity to relay operations. Details of the MOC and its operation can be found in [*Malin*, 1992]. In addition to its data relay function, the Mars Relay also performs Doppler measurements on the received signals. Data from these measurements, which are time tagged, can be analyzed to determine location on the surface of the transmitting station. This function is especially critical in for tracking atmospheric balloons which would be continually changing their location in undetermined ways, or penetrators like the New Millennium Deep Space Two (DS-2) Mars Microprobes, which have an undetermined landing location.

The MR consists of two main components, an antenna mounted on the nadir deck of the spacecraft and an electronics box mounted inside the spacecraft with power and control interfaces to the spacecraft and data interfaces to the Mars Orbiter Camera (MOC). The antenna is pictured in Figure 1 and the electronics box is shown in Figure 2. The MR antenna is a quadrifilar helix enclosed in a fiberglass mast approximately 80 cm in length. Four radiating elements of the quadrifilar helix are coupled to establish right-hand circular polarization (RHCP). The antenna is mounted on the nadir deck of the spacecraft in such a way to provide a nearly unobstructed view from limb to limb of Mars from the MGS mapping orbit altitude. The antenna is designed to provide peak gain (+2.2 dBi) towards the planet horizon while moderating the gain (-4.8 dBi) near nadir. The antenna gain pattern as a function of nadir angle for both transmit at 437.1 MHz and receive at 401.5275 MHz is illustrated in Figure 3. This pattern design maximizes communication time with stations on the surface while reducing the dynamic change in signal as the spacecraft passes over the surface station. Horizon to horizon relay communication is possible with this antenna pattern.

The Mars Relay broadcasts a beacon with an output power of approximately 1.3 watts (beginning of mission) at a center frequency of 437.1 MHz reference to an internal temperature compensated crystal oscillator (TCXO), with stability (Allan variance) of $2x10^{-10}$ over 1 s and 10^{-9} over 100 s (A. Ribes, CNES Memo, 13 October 1993). By selection of operating mode, the beacon signal can be modulated with one of four frequency modulated (FM) subcarriers, or with no modulation for continuous wave (CW). The subcarriers are designated RC1, RC2, RC3 for the three Request Command (RC) subcarriers each representing a lander identifier, and TC for the one Telemetry Command subcarrier. The corresponding offset frequencies for each FM subcarrier are given in Table 1. The activation of one of the subcarriers (lander identifier) is used to stimulate a response from a particular vehicle from the surface of Mars. This allows the selection of a specific vehicle for relay communication when more than one surface vehicle may be in view from the orbiting spacecraft.

The Mars Relay provides data communication at two uplink frequencies, 401.5275 MHz (designated F1) and 405.6250 MHz (designated F2) and at two data rates, 8 kilobits/second (designated R1) and 128 kilobits/second (designated R2). The exact data bit rates are given in Table 2. The MR contains a selectable Viterbi decoder which can automatically decode 7-1/2 convolutional coding on the received data stream. Four discrete command lines from the spacecraft command interface unit (CIU) allow the selection of any one of 16 operating modes. The different modes permit the selection of lander identifiers (RC1, RC2, RC3) or alternating combinations of identifiers, receive frequency (F1, F2), receive data rates (R1, R2), Viterbi decoder operation, and two test modes (CW, no beacon). The characteristics of each mode are given in Table 3.

A functional diagram of the Mars Relay is shown in Figure 4. Both the receiver and transmitter are connected to the Relay antenna through a diplexer which allows simultaneous transmit and receive operations. The receiver is based on a phase modulated (PM) carrier using NRZ/L-Biphase/PM data modulation with residual carrier. The received data are blocked and convolutionally coded to insure high integrity following reception. The convolutional code (7-1/2) is removed by an internal Viterbi decoder. Any block code, such as Reed Solomon 255/223/32, is removed on the ground. Basic RF and IF frequency sections are followed by a phase locked loop that performs carrier synchronization on the unmodulated component of the received signal. The receiver delivers a locally synchronized signal on the received carrier which drives the Doppler unit for frequency measurement. The bit synchronizer is based on a phase/frequency Costas Loop synchronized on the biphase data stream obtained after carrier demodulation. The detected NRZ data stream is digitized with a 4-bit analog-to-digital converter (ADC) prior to driving the integrated Viterbi decoder which removes the convolutional code using a soft decision algorithm (only the three most significant bits are used by the decoder). The decoder can also be by-passed with the most significant bit (MSB) being transmitted directly to the MOC buffer, which must have sufficient space to accept the coded data, stream at twice the bit rate.

The Mars Relay implements a robust communication protocol that does not depend on knowledge of the relative geometry, visibility and timing between the orbiting satellite and the landers. A request-to-send protocol is used in order to insure data retrieval without the risk of data loss. The protocol is based on a two-way up and down link protocol, illustrated in Figure 5. A time slot, referred to as Basic Time Transfer Sequence (BTTS), of 16 seconds duration, is implemented and driven by the Relay. Consecutive time slots are used to address the same or different landers (on an alternate mode basis) depending on the Relay mode. With each BTTS, the Relay broadcasts a beacon with a specific subcarrier, designating a specific lander. This signal is frequency modulated (FM) by a sine wave subcarrier (Table 1) whose frequency corresponds to one of three Lander identifiers (RC1, RC2, or RC3). When a lander detects the request signal modulated by its identifier, it responds by transmitting first an acquisition preamble consisting of a short tone of continuous wave (CW), then a pseudo random number (PN) sequence. The PN sequence is used by the Relay to lock up the bit synchronizer and internal convolutional decoder. The convolutional code is removed by Relay and the bit error rate (BER) is continuously estimated using this preamble. When the detected bit error rate is below a given threshold, the Request Command (RC) subcarrier is changed to the Telemetry Command (TC) subcarrier, signifying that the Relay has heard the lander with sufficient strength and is ready to receive data. When the lander detects the TC subcarrier in the beacon, the acquisition preamble (PN sequence) is stopped and the lander begins data transmission to the Relay.

Once the link is established, the Relay receives the lander telemetry data for approximately 14 seconds (depending on the link) within each BTTS. One second before the end of the current BTTS, the TC subcarrier is terminated by the Relay, breaking communication with the lander. During that one second interruption, the Relay inserts internal house keeping telemetry (HKTM) into the data stream flowing into the MOC buffer. Table 4 lists the internal analog telemetry and Table 5 lists the receiver status telemetry of the MR in the HKTM block reported at the end of each BTTS. Also included in the HKTM data are up to three time-tagged Doppler measurements of the received signal frequency. The Relay then recycles the protocol with the next BTTS time slot. If during transmission of telemetry the link quality degrades, increasing the bit error rate above a certain threshold, the MR stops broadcast of the Telemetry Command (TC) and waits until the beginning of a new 16-second BTTS to resume the communication sequence. In order to prevent loss of returned data when the MR drops the TC, the lander needs to save the last unit (block) of transmitted data and retransmit that same block at the beginning of the next BTTS contact. By assessing the link quality (BER) continuously during communications, this protocol permits relay operation in unknown and varying environments.

3. Mars Relay Testing In Flight

The Mars Relay internal house keeping telemetry (HKTM) reports on only a limited number of parameters and conditions (see Tables 4 and 5). As a result, the MR telemetry does not completely confirm its commanded state. Some indication of the current mode can be made from interpretation of the HKTM data. Table 6 lists the indicated MR modes for the given MR telemetry. However, because of this limited insight into the MR operating state and in order to confirm the post-launch functionality, tests between the Mars Relay and Earth-based stations were developed and carried out. Although the approximately 1-watt beacon signal level is low by deep space standards, the temperature compensated crystal oscillator (TCXO) within the MR provides a very stable frequency reference, permitting large Earth-based antenna facilities to detect the signal given sufficient integration time. The performance parameters permitted the involvement of the worldwide radio amateur community to listen for the UHF signals from the tests. Details of the amateur involvement can be found in [*Owen*, 1996] and [*Callas*, 1997]. Four in flight tests of the MR were performed beginning on 1996-11-24, 1999-07-14, 1999-11-

03 and 1999-12-01.

The SRI 46-meter Antenna at Stanford University, known as the Big Dish was employed to perform an independent verification of the MR. The Dish, a 45.7 m diameter antenna located in the foothills of Stanford University and operated by SRI International is a fully steerable, elevation/azimuth mounted paraboloid with an open mesh surface whose figure affords high efficiency aperture illumination up to frequencies of 2 GHz. The antenna pointing and control system is event driven and tracks at sidereal rates with azimuth and elevation position accuracies of 0.01 degree, or will slew at 2 degrees/sec with a position accuracy of 0.1 degree. Feeds are mounted at prime focus to the apex on a support tripod. The tripod can be lowered to the ground by a winch for ease of access to the apex. A photograph of the Dish is shown in Figure 6.

For the Mars Relay Flight Test beginning on 1996-11-24, a linear polarization UHF horn was installed at the prime focus feed on the Dish. The horn illuminated the 150-ft antenna aperture with an approximate 45% efficiency. The Dish's UHF transmitter, an IMAC Klystron, was capable of producing up to 30 kW of extracted RF power. For the Flight Test the tube was tuned to either the 401.5275 MHz (F1), or the 405.6250 MHz (F2). The uplink signal was derived from a phase modulated test station supplied by CNES. A manual switch was used to turn on and off the transmitted signal modulation with a second mechanical switch for selecting between transmit and receive at the Dish.

Over the duration of the two and a half day test ,with MGS approximately 5 million kilometers distance from Earth, the Mars Relay beacon signal and each of the four subcarriers (RC1, RC2, RC3 and TC) and unmodulated CW were observed by Stanford, consistent with the as-flown test plan. The confirmation of their detection was established using a realtime fast Fourier transform (FFT) generating a "waterfall" display (in frequency and time) of the down converted received signal. As an example, the display of the detection of Mode 12 is shown in Figure 7. The "stitch" pattern of the subcarrier FM harmonics from the alternating BTTS every 16 seconds between RC1 and RC3 is readily apparent. Brief pulses of pure carrier (CW) are also seen, as expected. With the model of the Mars Relay antenna pattern, an estimate of the received power at the input to the Mars Relay receiver was made for each of the radiated emissions from

Stanford during the Flight Test. Bit Error Rate (BER) analyses were performed by CNES on the Mars Relay data collected through the MOC from the Stanford transmissions. For the received power levels in the test, essentially no bit errors occurred. HKTM telemetry indicated nominal operations with a beacon output power of 1.3 watts.

At first, the detected modes in this test did not reflect the as-planned test sequence. It was determined from the observations that the ground command software that generated the Mars Relay commands had not been updated to reflect the as-integrated command interface for the Mars Relay on the spacecraft. The inversion of the logic levels and bit significance of the four command lines in the ground command software resulted in a different, but predictable, set of MR commands. No damage was incurred by the MR or the spacecraft. The MR ground command software has since been revised and verified for proper commanding. Details of this first flight test can be found in [*Callas*, 1997].

Three other in-flight tests with MGS, now in orbit at Mars, were performed with the MR and the SRI 46-meter Antenna. On 1999-07-14, the MR modes to support data return from the New Millennium Deep Space Two (DS-2) Mars Microprobes (MR Mode 03 and 06) were exercised. Because of the Earth-Mars range at the time of the test and the lack of realtime compensation in the Stanford system for received Doppler effects, the Big Dish, using a linear polarized feed, was unable to detect the MR signals. However, HKTM return via the MOC indicated nominal performance for the MR.

On 1999-11-03, one month prior to DS-2 relay support, the third flight test was performed. For this test and for the landed operations support, a new high-performance UHF feed was installed on the Big Dish. All previous UHF feed horns were all linearly polarized resulting in a 3 dB loss in performance with the right hand circularly polarized (RHCP) signals from the UHF systems at Mars (e.g., MR and the Mars Polar Lander). Furthermore, these linear horns under-illuminated the Big Dish aperture further lowering their performance.

A new UHF feed horn was designed and built, at SRI International, Menlo Park, California, for the UHF observations with the objective of improving the aperture illumination of the Dish, while reducing the response of the far side lobes which see the Earth and are a significant source of noise. A corrugated feed horn design provided uniform illumination of the central 60% of the aperture with a raised cosine taper to the aperture edge, a beamwidth of 1.2 degrees, and close-in side lobe response of -20 dB and far side lobe response of -40 dB beyond several beamwidths from the forward direction. The corrugated feed horn elements were cut from sheet aluminum with a laser trimmer and formed into circular segments and assembled together. A photograph of the horn, mounted at the apex of the prime focus tripod is shown in Figure 8. Profiles of compact astronomical radio sources verified that the corrugated horn met its design expectations, with a measured beamwidth of 1.2 degrees, and near side lobe of -20 dB.

A new receiver was assembled for the UHF observations consisting of a front end portion with a cavity filter and low-noise amplifier (LNA) chain, mounted directly on the horn at prime focus. The corrugated feed horn interfaced to a turnstile junction adapter with two circular polarization output ports. The turnstile junction has in fact four ports, two of which were terminated with tuning stubs that adjusted to match the RF response at both 437.1 MHz and 401.5 MHz. These two frequencies were matched at both output ports, with the polarization of the ports opposite from each other. Swapping the tuning stubs swapped the polarization of the ports. A filter-LNA chain was mounted on each port, one for right-hand circular polarization (RHCP), and the other for left-hand circular polarization (LHCP). The observations of the MGS/MR beacon were carried out with the 437.1 MHz filter-LNA chain connected to the RHCP port. A second, 401.5 MHz filter-LNA chain was connected to the LHCP port although the polarization of the chains could be swapped by swapping the tuning stubs. Since the DS-2 Microprobes use linear polarized antennae, the Dish feed could simultaneous observe the MR beacon at 437.1 MHz with right-hand circularized polarization on one port and the DS-2 Microprobes at 401.5 MHz with left-hand circular polarization on the other port but with an expected -3 dB polarization loss.

The outputs of the filter-LNA chains were connected at prime focus to two RF transport lines, B1 and B2, which terminated inside the operations and control house underneath the Dish. The connectivity of feed to the filter-LNA chains and the lines is shown in the schematic in Figure 9. By using low loss cavity filters and uncooled amplifiers, the noise figure for each polarization obtained with this arrangement was 0.9 dB, with an equivalent noise temperature below 70 K.

This included feed loss and side lobe contributions as well. Inside the control house the lines B1 and B2, were connected to a second RF filter-LNA chain, as shown in Figure 9. The output of these chains consisted of two exclusive RF signals centered at 437.1 MHz and 401.5 MHz respectively, each with a bandwidth of 2 MHz and sufficient roll off that placed the power from the 437.1 MHz filters below the noise floor of the system at the transition edge of the 401.5 MHz filters, and vice versa. At this point the two filter-LNA chains were combined in a splitter, as shown in Figure 9, into a single RF signal as input to the downconverter. Downconversion proceeded in two heterodyne stages. The first stage used a local oscillator (LO) whose function was to select between the two RF frequencies which was done by simply choosing the frequency of LO-Ia. The first mixing stage had the additional function of Doppler compensation performed by adding a second frequency LO-Ib, from a swept signal generator whose frequency was programmed. The programmed frequencies were derived from a list of Doppler predicts, themselves produced with JPL Navigation software tools containing up to date knowledge of Earth and Mars ephemeris as well as the MGS orbit. The two frequencies LO-Ia and LO-Ib, were mixed together and bandpass filtered, to produce the LO for the first RF mixing stage. The resultant IF, was then mixed to baseband in parallel In-phase (I), and Quadrature (Q), channels completing the function of the downconverter.

The spectral analysis of the UHF signals was performed on the I and Q channels using three parallel digital signal processing (DSP) systems. The first was a real time but low sensitivity system that was used to monitor the RF quality, system temperature and RFI environment. The second was a hardware DSP-based fast Fourier transform (FFT) spectrum analyzer used to archive integrated spectra with high sensitivity, 1 Hz resolution bins, but narrow processing bandwidth. The third was a wider band (typically 50 kHz/channel) sampler used only to record the samples in the I and Q channels for off line, non-realtime post-processing.

During the test observations in November of 1999, Mars was tracked by the Dish shortly after rising on the eastern horizon, for approximately 10 hours. MGS maintains nadir pointing during its orbit. Since the MR antenna has a beam pattern with an off-nadir enhancement, the effect of nadir pointing produced a period of favorable orientation during each orbit. During this period, the Earth was in the positive gain direction of the MR antenna. This condition persisted for several tens of minutes every orbit. During this interval signals from the UHF receiver were compensated for MGS orbital and Earth Doppler then mixed to baseband where a digital signal processor computed Fourier transform spectra to a resolution of 1 Hz. These spectra were archived to disk for post-processing and offline analysis.

The search for the MR beacon involved looking for a signal in a single 1Hz channel in the archived spectra during the favorable portion of the orbit and if found, comparing that and a few neighboring channels with channels in the spectra from the rest of the orbit to see if the signal went away. The Doppler compensation in the UHF receiver afforded an additional verification where any candidate signal should appear stable in frequency. Since ground based, terrestrial radio frequency interference (RFI) is apt to be frequency stable, the Doppler compensation would produce a drifting signal in the archived spectra. Many such artifacts, drifting in frequency, were indeed observed and the ability to classify them as RFI was essential in the MR beacon detection.

At first, the detailed examination of the archived spectra for the November 1999 observations of MGS at Mars produced no suitable candidate signals for the MR beacon. After checking the antenna pointing accuracy, the system temperature calibration and the command sequences to MGS/MR, and finding all systems were performing correctly, a 64 second error was found after the fact in the timing synchronization for the UHF receiver's Doppler compensation. The timing error spread the signal over many 1Hz channels and degraded sensitivity correspondingly. This effect was exactly calculable, so a correction was formulated and applied off-line to the data. When this error was corrected, the MR signal was clearly resolved. Figure 10 contains the resolved Mars Relay CW spectrum after the correction was applied.

A fourth flight test was performed on 1999-12-01 following the MR activation in support of landed operations for DS-2 and MPL. The MR was set to is pure carrier Mode 15 (CW) for two days. During this time, the MR CW beacon was consistently observed by the SRI Big Dish. The successful detection of the Mars Relay beacon with the upgraded facilities of the Big Dish and a review of the internal HKTM telemetry certified Mars Relay to be fully functional and ready to support landed operations at Mars. Table 7 summarizes the verification of the MR modes achieved either, by internal HKTM data or by independent detection with the SRI Big Dish during the flight tests and subsequent landed operations. With the exception of MR Modes 04 and 07, which were not tested in flight, all other modes were confirmed, although Modes 01 and 02 were not confirmed uniquely. Importantly, Modes 03 and 06 used by DS-2 and Mode 14 used by MPL were confirmed.

4. Landed Operations Support

The Mars Relay on MGS was employed to provide exclusive data return from the two New Millennium DS-2 Mars Microprobes and backup data return for the Mars Polar Lander. Additionally, the SRI 46-meter Antenna with its upgrade and improved sensitivity could possibly observe the signals from the Microprobes or the Polar Lander directly. Table 8 summarizes the link analysis of UHF detection of the Mars Relay, the Microprobes and the Polar Lander by the SRI 46-meter Antenna at the time of lander and probe arrival at Mars on 1999-12-03. The analysis indicated that the MR CW signal and FM subcarriers would be detected after just a few seconds of integration at the Big Dish. The MPL signal delectability would depend on the stability of its transmit frequency. However, any detection of the DS-2 probes by the Big Dish would require off-line processing of the recorded data owing to their expected weak signal and instability of their internal oscillators.

The Mars Microprobes were designed to exploit MR protocol using the low data rate (R1) and frequency F1 (401.5275 MHz). Each probe was assigned a unique lander identifier, RC2 for Probe 1 and RC3 for Probe 2. MR Doppler measurements would be post-processed to locate the Microprobes on the surface of Mars. To increase the likelihood of detecting the probes in a harsh communication environment, the probes were designed to periodically insert 16 seconds of pure carrier (CW) into the transmission protocol. Since the MR receiver can lock up on a pure carrier signal, this increased the link margin by 6 dB over data modulated communication from the probes. Though no DS-2 telemetry data is communicated during these brief CW periods, if detected by the MR, they would provide confirmation the probe (or probes) survived landing.

The sequencing strategy for DS-2 data return consisted of three concurrent mini-sequences on

MGS for the operation of the Mars Relay (MR). This strategy is illustrated in Figure 11. The chart contains in the background, the DS-2 view period opportunities by MGS (and Stanford) for the first 5 sols. The three mini-sequences (shown as foreground color bars) are designated Baseline Sequence (light blue), Probe 1 Backup (magenta), Probe 2 Backup (green). All three sequences were pre-built loaded on the spacecraft and active before DS-2 Entry, Descent and Landing (EDI) on 1999-12-03. All three sequences cover every pass opportunity during Sols 0,1 and 2 with the baseline sequence continuing out for 14 sols. Listen-only opportunities (orange) for DS2 are established around the time of the autonomous transmit windows for each DS-2 probe.

Each pass opportunity was sequence to be exactly 24 minutes (90 BTTS). The 24-minute pass provided horizon to horizon coverage with additional timing margin for orbit and landing location uncertainties. On Sol 0, every pass alternated between Probes 1 and 2 every 2.4 minutes (9 BTTS). On all subsequent sols, only one probe at a time was queried during each 24-minute pass. During the first sol's sequences, each contingency sequence has commands that are intermingled during each 24-minute pass, providing alternating communication every 2.4 minutes (just as in the baseline sequence passes). If one of the contingency sequences is terminated on the first sol, the other sequence effectively covers that remaining probe for the full 24 minutes of the pass.

When successful communication and data return is established from a given probe, a single command can be radiated to MGS (during a MGS uplink window) to terminate that probe's backup sequence. If both probes are successful, then both backup sequences can be terminated (by real time command) and the baseline sequence will communicate daily with each probe for the balance of the nominal 14-sol period. If successful communication is not established with either probe, then all three mini-sequences can be left to clock out and attempt to communicate with each probe on every pass for the first 3 sols, then the baseline for the remaining 11 sols.

The sequenced relay operations on MGS for DS-2, beginning on 1999-12-03, executed as designed with the MOC performing coordinated readouts of the MR. The MOC performed readouts of each DS-2 relay opportunity for the first three days of expected DS-2 landed operations. However, the returned MR data through the MOC contained only internal HKTM data. The HKTM data did not indicate any receiver lock events. No DS-2 data were received by the MR. The HKTM data did indicate nominal MR performance. Independent and direct detection of the MR beacon and both lander identifier subcarriers (RC2 and RC3) by the SRI 46-meter Antenna confirmed nominal beacon operation. Figure 12 shows the two spectra collected by the Big Dish exhibiting the Mode 03 and Mode 06 subcarriers at the expected frequency and signal level, and occurring at the correct point in the MGS orbit. Subsequent, off-line processing of data at 401.5275 MHz recorded at the Big Dish found no evidence of the DS-2 signals. Failure of both DS-2 probes on the surface of Mars is believed to explain the absence of data in the MR return.

The Mars Polar Lander (MPL) was planned to land near the South Pole of Mars along with DS-2 on 1999-12-03. The Mars Relay and MGS were coordinated to provide backup relay support for MPL. MPL would use X-band directly to the Deep Space Network (DSN) as its primary communication path. Additionally, MPL carried a UHF relay system with a mode compatible with the Mars Relay protocol, (Mode 14 with frequency F1, data rate R2 and lander identifier RC1). When repeated attempts over X-band failed to establish communications with MPL following landing, the MR was sequenced to attempt UHF communication with the lander beginning on 1999-12-06. The UHF relay attempts were tried over several days. The SRI 46-meter Antenna also attempted to detect any UHF signals directly from the lander. No UHF signals were detected from MPL.

Although the MR HKTM data, returned by the MOC, showed no indications of receiver lock, occasional bit synchronizer lock events occurred. Subsequent tests were performed on the MR in Mode 14 when MGS was away from the South Pole also showed occasional bit synchronizer lock events (without receiver lock). It has been determined that at the higher data rate (R2), spurious bit synchronizer lock events can occur due to the lower synchronizer threshold at the higher rate.

As part of the investigation of these occasional bit sync events, the MR was cycled through several of its modes. When Mode 13 (F2, R1) was activated, several receiver lock events occurred. Neither DS-2 nor MPL were implemented to use frequency F2. Furthermore, these receiver lock events were observed to occur when MGS was away from the South Pole of Mars, insuring that these events were not the result of actual signals. No receiver lock events were observed in any of the MR Modes that use frequency F2 and data rate R2. It is concluded that the observed receiver lock events are due to a localized jamming signal near in frequency, originating from the MGS spacecraft itself. Table 9 summarizes all the HKTM status bits observed from the MR between 1999-11-29 and 2000-03-06. As noted, no receiver locks were ever observed with Modes 03 and 06 (F1, R1) for the DS-2 Microprobes, or with Mode 14 (F1, R2) for MPL.

5. UHF Signals From Mars

Although the MR in orbit or the SRI Big Dish Antenna detected no signals from the surface of Mars on Earth, the Big Dish routinely detected the Mars Relay beacon. Using the upgraded horn and receiver, the signals were detected in the narrow band receiver system of the Dish. Use of this system for signal detection required that the absolute frequency of the MR beacon was known to better than 1 kHz. Substantial evidence existed at the time of these observations indicating that the rest frequency of the MR was within a few hundred Hertz of 437.099700 MHz. For example, the aging rate of the MR crystal reference was accurately measured before flight and the MR frequency was itself accurately determined in the 1996 flight test [*Callas*, 1997]. Both measurements provided a basis for estimating the MR frequency to within a few tens of Hertz. Thus on the strength of this knowledge, the baseband I and Q channels were centered in frequency to 437.099300 MHz, with the expectation that the MR signal would be found approximately 400 Hz from DC.

The MR signal was additionally expected to be stable to within at least 1 Hz, over tens of minutes. Thus a signal detection bandwidth of 1 Hz was chosen for the search of the MR beacon. Accordingly, the I and Q channels were low pass filtered with a 1 kHz cutoff, and sampled at 2.0 ksamples/sec. Those sample were input to digital signal processing (DSP) hardware, configured to process successive 2048 sample sequences into 2k-pt FFT's with 1 Hz bins. The power in each bin was computed and sets of 5 FFT's were averaged with the DSP delivering a 2k-pt integrated spectrum once every 5 seconds. These spectra were transferred from the DSP to a PC that served as a controller. The PC collected sets of 12 spectra together and placed each set on its hard drive for interim storage. A Sun-Ultra workstation was networked with the PC controller and shortly after each spectral set was produced the Sun transferred the spectra to an archive in its file system. The search for the MR beacon signal was performed on the spectra in this archive.

The MR beacon was easily found during the time intervals in the MGS orbit with favorable orientation of the MR antenna toward Earth. This occurs twice each 118-minute orbit of MGS. The duration of favorable geometry persisted for tens of minutes and within this interval the MR beacon is most easily observed by for example, integrating the archived spectra by only a few tens of seconds, i.e. averaging successive groups of 4 to 8 spectra together. The MR beacon appears in these averages with a signal to noise ratio (SNR), of typically 10 dB. A waterfall plot (in time and frequency) of a sequence of such spectra is displayed in Figure 13, where the MR signal is seen to change slightly in frequency over the duration of the interval.

Mars was observed using The Dish and its UHF feed and receiver on several days. Specific dates along with the Earth-Mars range and local elevation angles are given in Table 10. On seven of these dates the MR was in CW mode (Mode 15) and during the approximately 10 hours that Mars was above the horizon, the nearly 2 hour orbit of MGS provided 4 or 5 opportunities to detect the MR beacon during a period of favorable geometry. Each observing day during at least one of these periods the Dish UHF receiver with active Doppler compensation was configured for the MR and spectra were collected and archived. In every one of those cases the MR signal was detected in the archived, integrated spectra from the DSP-PC system processing the I and Q channels in the narrowband mode. Because of the great distance involved these detections by the Big Dish represented the first time that a UHF signal had been detected in excess of two astronomical units (AU).

The MR signal observed by the Dish displays some unexpected features. In Figure 13, the signal's frequency appears to be changing with time. This same behavior is repeated in other CW beacon observations, as shown in Figure 14. Here the MR signal's frequency evidently 'rocks' back and forth as the MGS spacecraft orbits Mars, at least over the portion of the orbit during which the MR signal is detectable. This frequency motion could be a residual Doppler produced by unaccounted motion of the spacecraft as yet unknown but this is unlikely since the observed signal's frequency rate of change, (< 0.03 Hz/sec), would be ascribed to spacecraft accelerations of such magnitude (~ 0.03 g). Insight into the mystery can be gained by examining the orbital geometry of MGS. Figure 15 shows the Earth view of the MGS orbit about Mars on 1999-12-02. As the spacecraft passes through the period of favorable orientation the spacecraft moves from a high northern Martian latitude to a southern latitude at the end of this period. Furthermore, the raypath from the MR antenna to Earth first descends from orbital altitude (~ 380 km) down toward the Martian surface nearly into a full occultation condition, and then ascends back up to the orbital altitude. The altitude of the raypath is identified as the distance along a radial vector from the surface to the perpendicular intersection at the raypath. Using the archived spectra time tags to identify the position of MGS in Martian orbit, the MR signal can be displayed as a function of raypath altitude.

Figure 16, shows an observation from December of 1999. The MR signal is plotted together with the raypath altitude above the surface. In this profile the vertical scale is time as in the previous two figures (Figure 13 and 14) but in addition the vertical scale is annotated with the height of the raypath above the Martian surface. The profiles plotted this way align the profiles according to the altitude of the raypath above the Martian surface and reveal a common behavior as a function of altitude. This behavior could be the effects of a Martian ionosphere. The abrupt change in the signal frequency could indicate the presence of ionization in layers similar to structure common in the Earth's ionosphere. Work is ongoing that will invert the observed frequency profiles and obtain a model of refraction and electron density.

6. Conclusion

The Mars Relay was utilized for primary data return of the New Millennium Deep Space Two Micro Probes and backup data return for the Mars Polar Lander. No data were returned from either landed system. Internal Mars Relay house keeping telemetry (HKTM) was returned and indicated an active and functioning relay system. Direct and independent detection of the Mars

Relay beacon by the SRI 46-meter Antenna further reinforced the Mars Relay functionality at the time of landed operations at Mars. The detection of the Mars Relay beacon from Mars represents the first time that a UHF signal had been transmitted and received in excess of two astronomical units (AU). The Mars Relay remains a viable telecommunication resource for data return from the surface of Mars.

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References

Albee, Al. L., Palluconi, F. D., Arvidson, R. E., Mars Global Surveyor Mission: Overview and Status, *Science*, *279*, 1671-1672, 13 March 1998.

Callas, J. L., Mars Relay Flight Test Final Report, JPL D-14423, 1997 March 14.

Malin, M. C., Danielson, G. E., Ingersoll, A. P., Masursky, H., Veverka, J., Ravine, M. A., and Soulanille, T. A., Mars Observer Camera, *J. Geophys. Res.*, *97*, 7699-7718, 1992.

Owen, M. R. and Callas, J. L., DXing enroute to the Red Planet, *QST*, *80*, 44-45, January 1996.

Ribes, A., Lander Pooling and Data Collection Principle for Future Planetary Missions, 46th International Astronautical Congress, IAF-95-Q.4.01, Oslo, October 1995.

Table 1. Subcarrier Offset Frequencies

Subcarrier	**Offset Frequencies**
RC1	1484.06 Hz
RC2	1137.78 Hz
RC3	1028.11 Hz
TC	1376.34 Hz

Table 2. Data Bit Rates

Mode	**R1**	**R2**
F1	8003 bits/s	128038 bits/s
F2	8085 bits/s	129345 bits/s

Table 3. Mars Relay Operational Modes

Mode Number	CMD3	CMD2	CMD1	CMD0	Lander	Beacon	Data Rate	RF Freq	Viterbi Decoder	Calling Order BTTS
M1	1	1	1	1	L1 only	ON	R1	F1	ON	RC1/TC
M2	1	1	1	0	L1 only	ON	R1	F1	OFF	RC1/TC
M3	1	1	0	1	L2 only	ON	R1	F1	ON	RC2/TC
M4	1	1	0	0	L2 only	ON	R1	F1	OFF	RC2/TC
M5	1	0	1	1	L1/L2	ON	R1	F1	ON	RC1/TC - RC2/TC
M6	1	0	1	0	L3 only	ON	R1	F1	ON	RC3/TC
M7	1	0	0	1	L3 only	ON	R1	F1	OFF	RC3/TC
M8	1	0	0	0	L3 only	ON	R2	F2	ON	RC3/TC
M9	0	1	1	1	L1/L2	ON	R1	F1	OFF	RC1/TC - RC2/TC
M10	0	1	1	0	L1/L3	ON	R1	F1/F2	ON	RC1/TC - RC3/TC
M11	0	1	0	1	L1/L3	ON	R1	F1/F2	OFF	RC1/TC - RC3/TC
M12	0	1	0	0	L1/L3	ON	R2	F1/F2	ON	RC1/TC - RC3/TC
M13	0	0	1	1	L3 only	ON	R1	F2	OFF	RC3/TC
M14	0	0	1	0	L1 only	ON	R2	F1	ON	RC1/TC
M15	0	0	0	1	Test 1	ON	R1	F1	ON	no modulation
M16	0	0	0	0	Test 2	OFF	R1	F1	OFF	NA

Table 4. Mars Relay Internal Analog Telemetry

Byte	Telemetry Channel	LSB Value	Range
1	Secondary Voltage -10 V	60 mV	NA
2	Secondary Voltage +10.2 V	60 mV	NA
3	Secondary Voltage 5 V	25 mV	NA
4	Secondary Voltage 5.2 V Logic	25 mV	NA
5	Secondary Voltage 5 V Viterbi	25 mV	NA
6	Internal Temperature	0.5 C°	-30°C to 70°C
7	Received RF Signal AGC	0.2 dB	NA
8	UHF Transmitted Power Output	10 mW	NA

Table 5. Mars Relay Internal Receiver Status

Bit	Status	Bit = 0	Bit = 1
0	Receiver	Unlocked	Locked
1	Bit Synchronizer	Unlocked	Locked
2	Viterbi	Unlocked	Locked
3	Receive Frequency	F2	F1
4	Data Rate	R1	R2
5	Viterbi Decoder	Non-operational	Operational
6	Viterbi Power Supply	Off	On
7	Anomaly	No	Yes

Table 6. MGS Mars Relay House Keeping Telemetry (HKTM) Indicated Modes

MR HKTM Status Bits				Indicated MR Mode(s)
Beacon	**Data Rate**	**Frequency**	**Viterbi**	
On	R1	F1	On	Mode 01 Mode 03 Mode 05 Mode 06 Mode 15
On	R1	F1	Off	Mode 02 Mode 04 Mode 07 Mode 09
On	R2	F2	On	Mode 08
On	R1	F1/F2	On	Mode 10
On	R1	F1/F2	Off	Mode 11
On	R2	F1/F2	On	Mode 12
On	R1	F2	Off	Mode 13
On	R2	F1	On	Mode 14
Off	R1	F1	Off	Mode 16

Table 7. Mars Relay Mode Confirmation with Associated Test Dates

MR Mode	Confirmation by HKTM	Confirmation by Stanford	Note
Mode 01	Not Uniquely (2,3,4)		
Mode 02	Not Uniquely (1)		
Mode 03	Not Uniquely (2,4)	Yes (4)	DS2 Mode
Mode 04	Not Tested		
Mode 05	Not Uniquely (4)	Yes (1)	
Mode 06	Not Uniquely (1,2)	Yes (1,4)	DS2 Mode
Mode 07	Not Tested		
Mode 08	Yes (1)	Yes (1)	
Mode 09	Not Uniquely (4)	Yes (1)	
Mode 10	Yes (4)		
Mode 11	Yes (4)		
Mode 12	Yes (1,4)	Yes (1)	
Mode 13	Yes (4)		
Mode 14	Yes (3)	Not Yet (4)	MPL Mode
Mode 15	Not Uniquely (2,3,4)	Yes (1,3,4)	CW Mode
Mode 16	Yes (1,3)		No RF Mode

1. Mars Relay UHF Flight Test 1996-11-24
2. Mars Relay Checkout 1999-07-14
3. Pre-EDL/EDI MR Checkout 1999-11-03
4. MPL/DS2 Landed Operations 1999-12-01

Table 8. Earth-Mars UHF Link Analysis

Transmission Station:	MGS	MGS	DS-2	MPL
Frequency [Hz]	437100000	437100000	401527500	401527500
Wavelength [m]	0.6859	0.6859	0.7466	0.7466
Modulation	CW	FM	CW	FSK
Transmit Power [W]	1.07	1.07	0.479	14.0
Transmit Power [dBm]	30.3	30.3	26.8	41.5
Circuit Losses [dB]	-0.5	-0.5	-0.4	-1.0
Antenna Gain [dBi]	0.0	0.0	-3.0	-1.0
EIRP [dBm]	29.8	29.8	23.4	39.5
Range [m]	2.538E+11	2.538E+11	2.538E+11	2.538E+11
Space Losses [dB]	-253.3	-253.3	-252.6	-252.6
Atmospheric Losses [dB]	0.0	0.0	0.0	0.0
Receiving Station:	**Stanford**	**Stanford**	**Stanford**	**Stanford**
Antenna Diameter [m]	45.7	45.7	45.7	45.7
System Efficiency	0.60	0.60	0.60	0.60
Antenna Effective Area [m2]	985.0	985.0	985.0	985.0
Antenna Gain [dB]	44.2	44.2	43.5	43.5
Half Power Beam Width [°]	1.1	1.1	1.2	1.2
Feed Losses [dB]	-0.2	-0.2	-0.2	-0.2
Polarization Losses [dB]	-1.0	-1.0	-3.0	-1.0
Misc Losses [dB]	-0.1	-0.1	-0.1	-0.1
Modulation Loss [dB]	0.0	-6.4	0.0	-6.0
Received Power [dBm]	-180.7	-187.1	-189.0	-177.0
System Temperature [K]	68	68	68	68
Noise Density [dBm/Hz]	-180.3	-180.3	-180.3	-180.3
Search Bandwidth [Hz]	1.0	1.0	1.0	1.0
Noise Power [dBm]	-180.3	-180.3	-180.3	-180.3
Received SNR [dB]	-0.4	-6.8	-8.8	3.3
SNR [dB] after 16 s	5.6	-1.4	-2.8	9.3
SNR [dB] after 64 s	8.7	1.6	0.3	12.3

Table 9. Summary of MR Status Bit Events

	F1	**F2**
R1	0 Receiver Locks 0 Bit Syncs out of 3777 BTTS	68 Receiver Locks 0 Bit Syncs out of 117 BTTS
R2	0 Receiver Locks 143 Bit Syncs out of 1215 BTTS	0 Receiver Locks 0 Bit Syncs out of 58 BTTS

Table 10. Summary of UHF Observations of Mars by the SRI 46-meter Antenna

Date	**Maximum Local Mars Elevation [°]**	**Earth-Mars Range [km]**
1999-12-01	32.2	252165532.0
1999-12-02	32.4	252962757.4
1999-12-03	32.6	253758598.1
1999-12-04	32.8	254556906.8
1999-12-05	33.0	255358607.1
1999-12-06	33.2	256158480.8
1999-12-07	33.5	256956019.1
1999-12-10	34.1	259359869.5
1999-12-14	35.0	262564972.2
1999-12-18	36.0	265774908.8
2000-01-04	40.6	279507549.5
2000-01-05	40.9	280320658.6
2000-01-26	47.2	297368390.7
2000-01-27	47.5	298179660.6
2000-02-04	50.0	304661188.3
2000-02-08	51.3	307133056.0

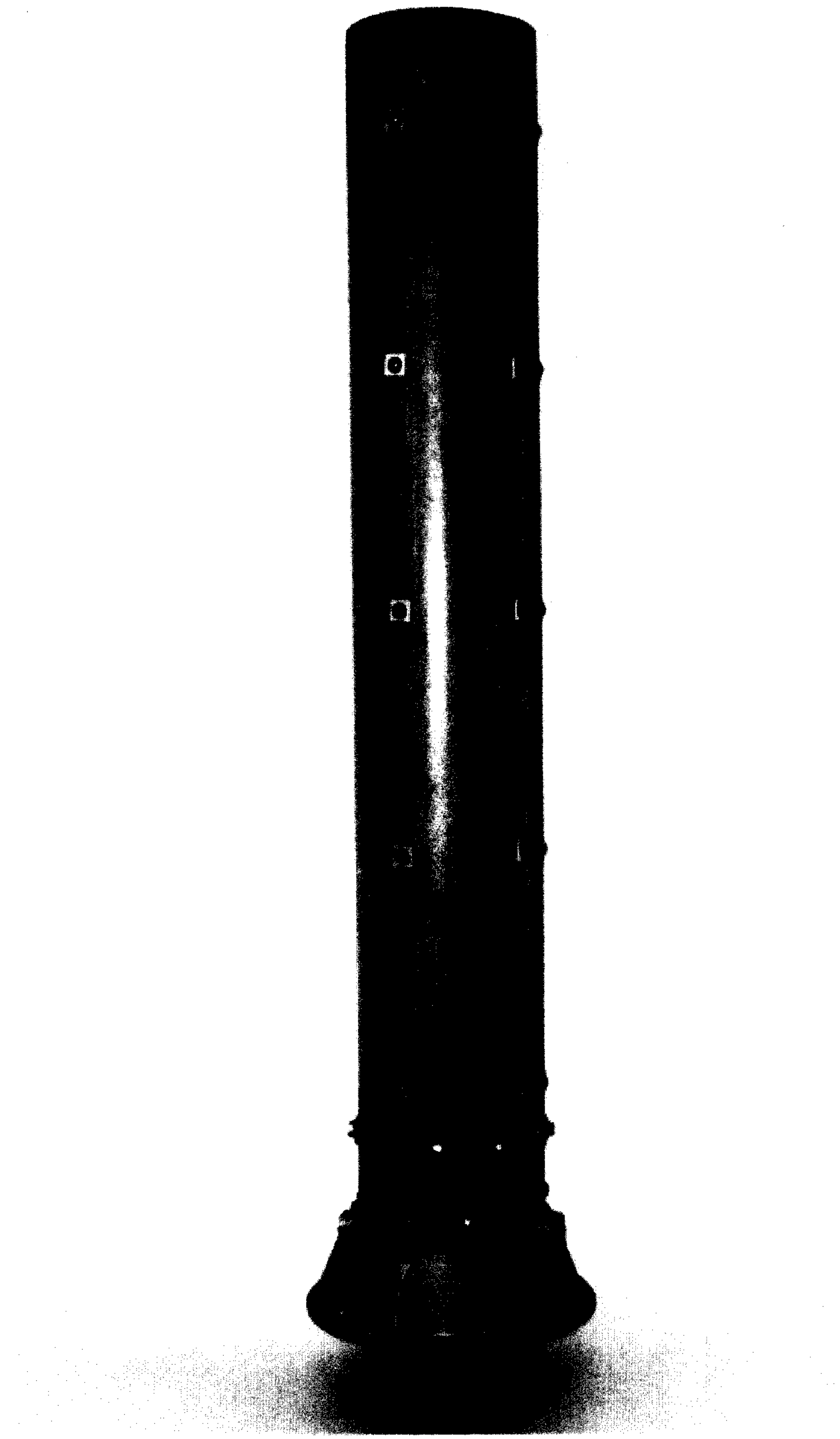


Figure 1. The Mars Relay Antenna. Four radiating elements inside the 80-cm fiber glass mast form the quadrifilar helix antenna. The antenna is mounted on the nadir deck of MGS with a nearly unobstructed horizon-to-horizon field of view.

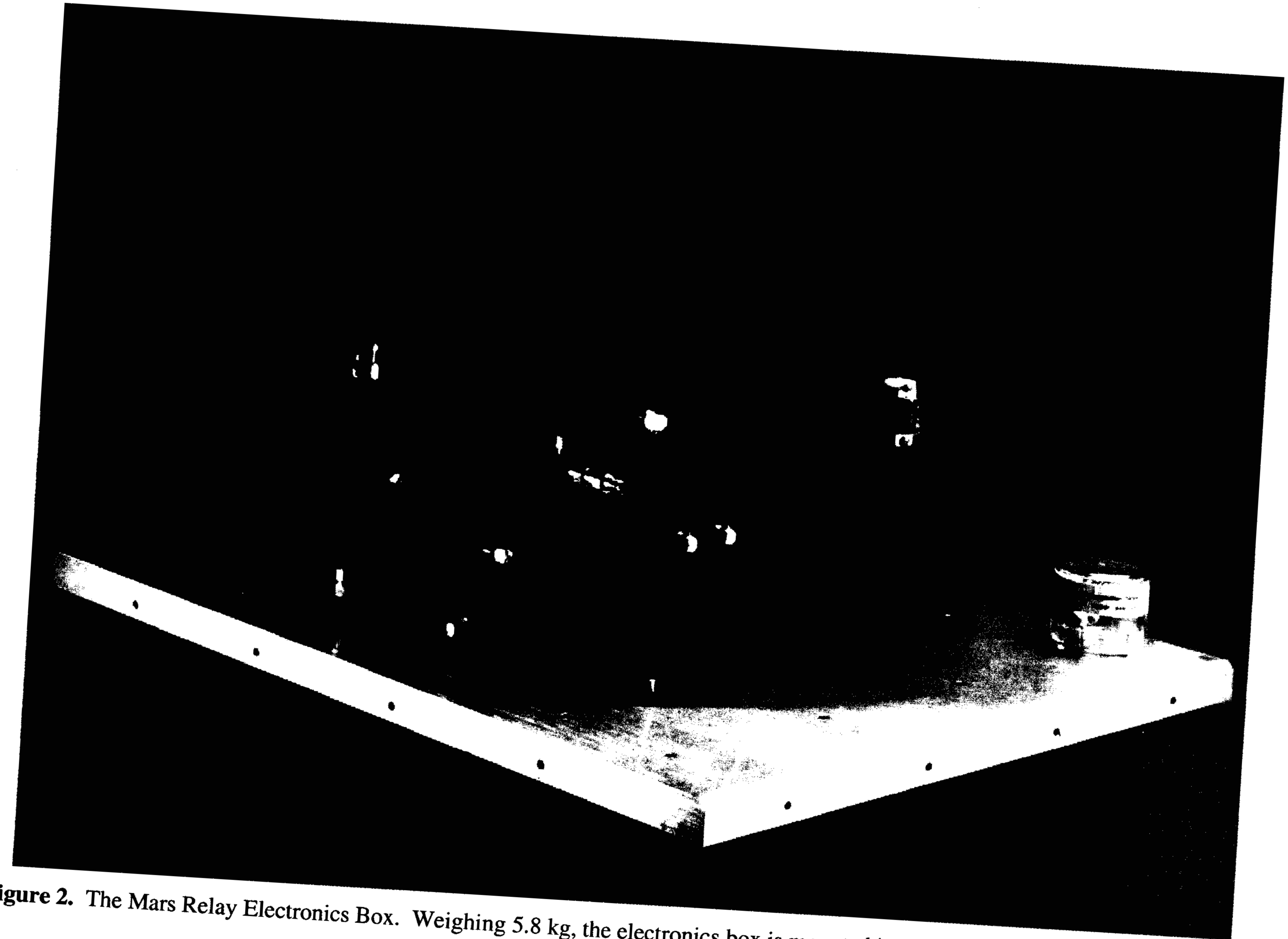
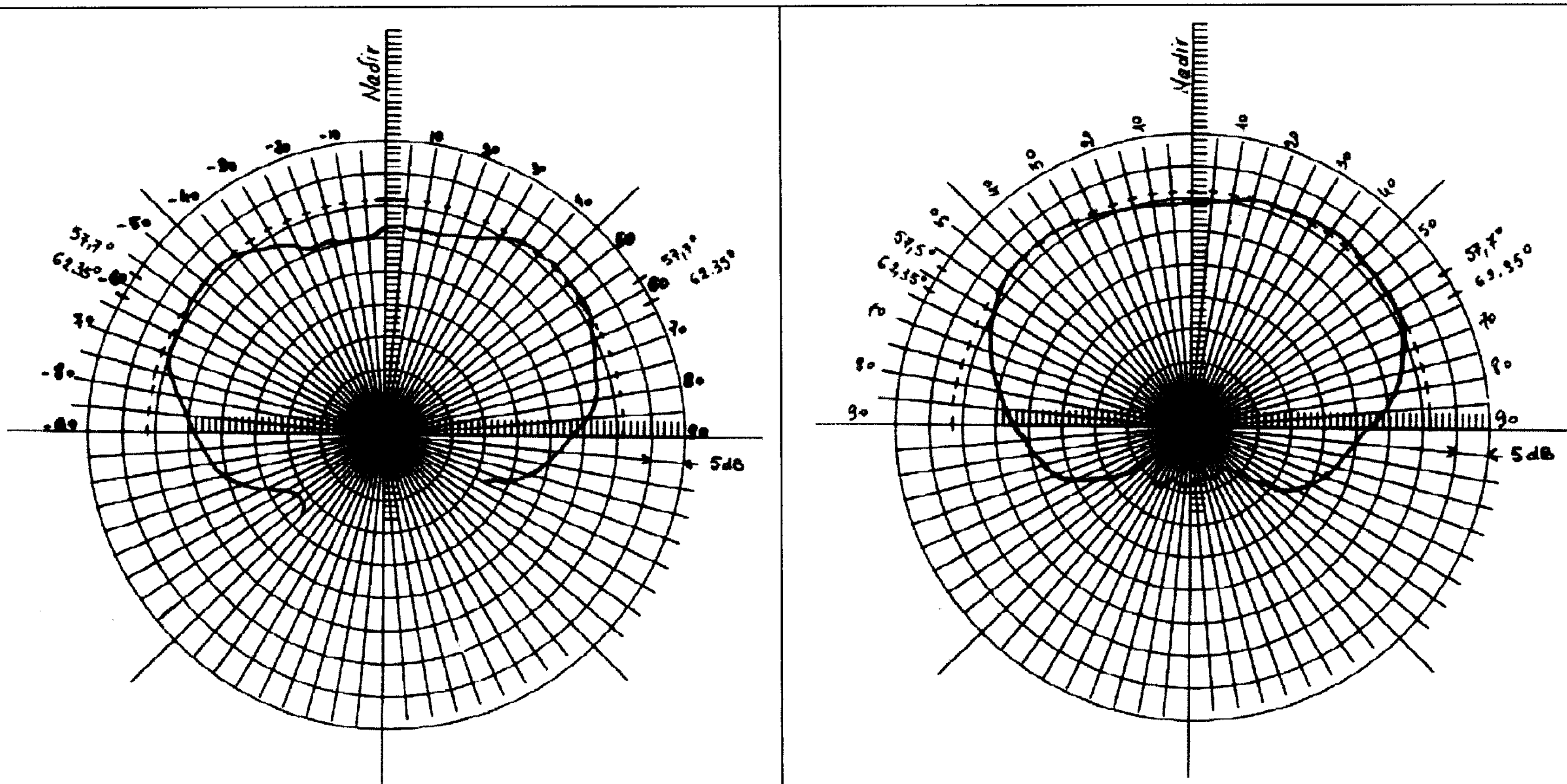


Figure 2. The Mars Relay Electronics Box. Weighing 5.8 kg, the electronics box is mounted inside the MGS spacecraft bus.



Transmission at 437.1 MHz

Reception at 401.5275 MHz

Figure 3. The Mars Relay Antenna Pattern. The figure on the left shows the worst-case antenna gain pattern (in elevation) for transmission at 437.1 MHz. The figure on the right shows the worst-case antenna gain pattern (in elevation) for reception at 401.5 MHz.

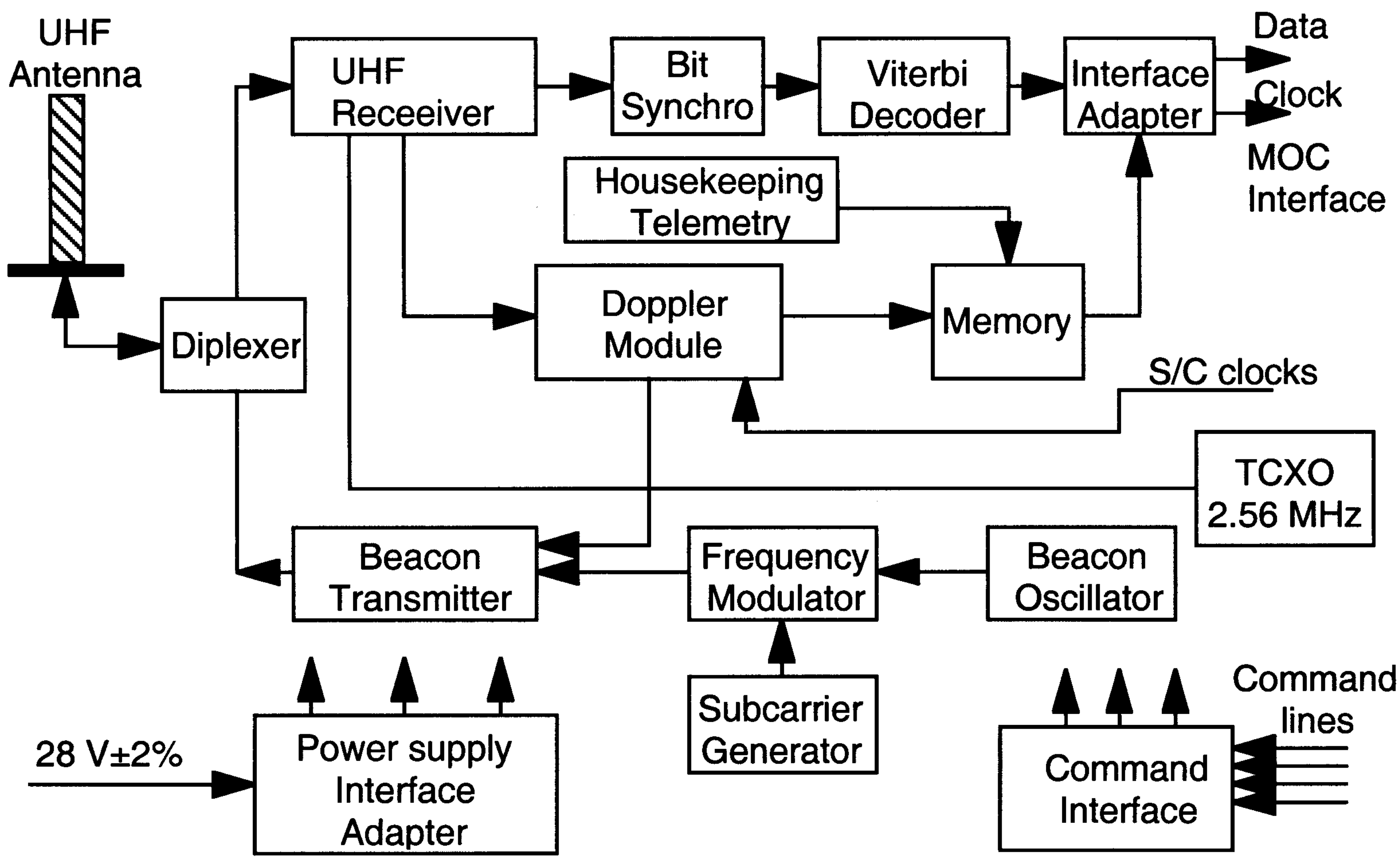


Figure 4. Mars Relay Functional Diagram

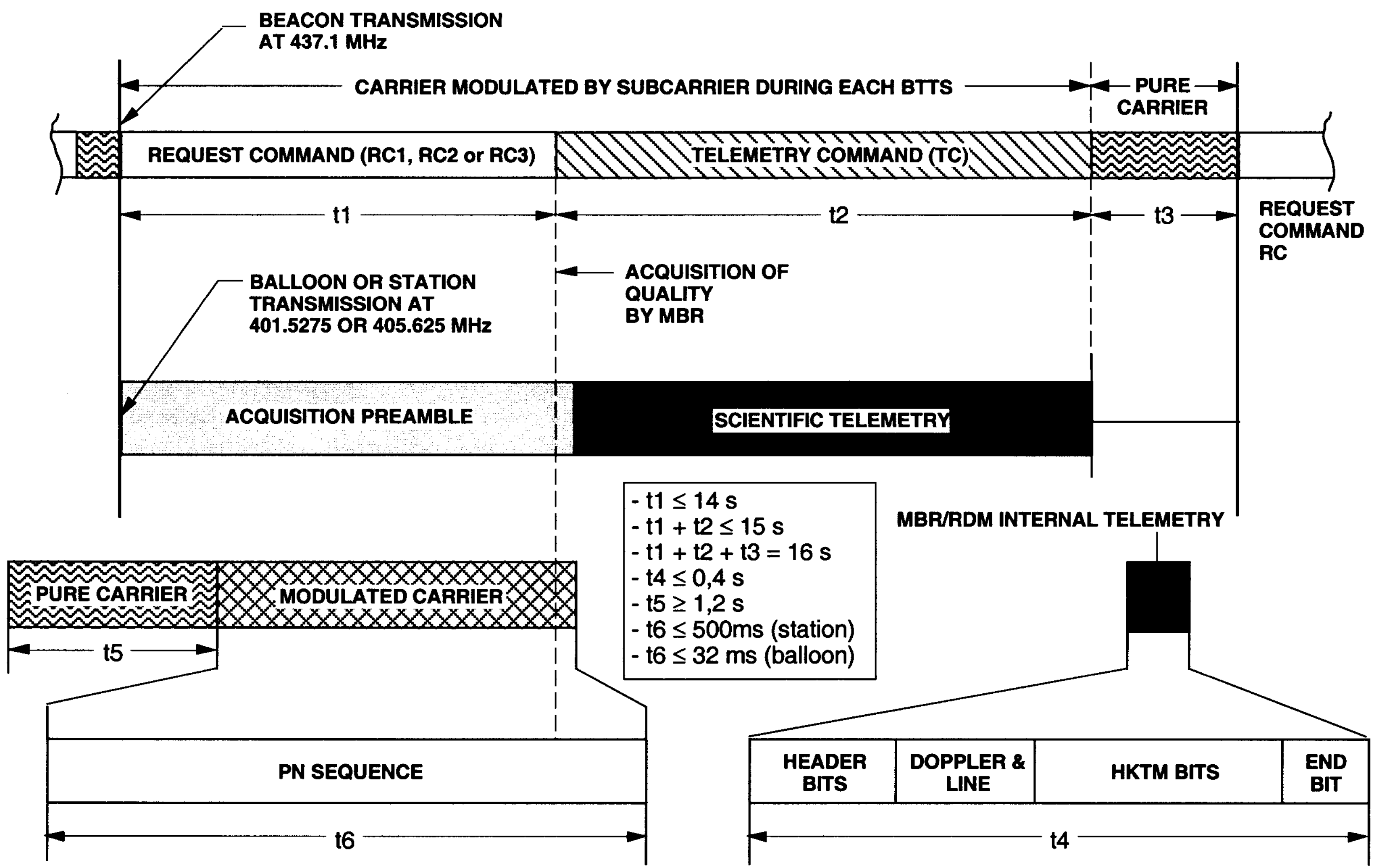


Figure 5. Mars Relay BTTS Link Protocol

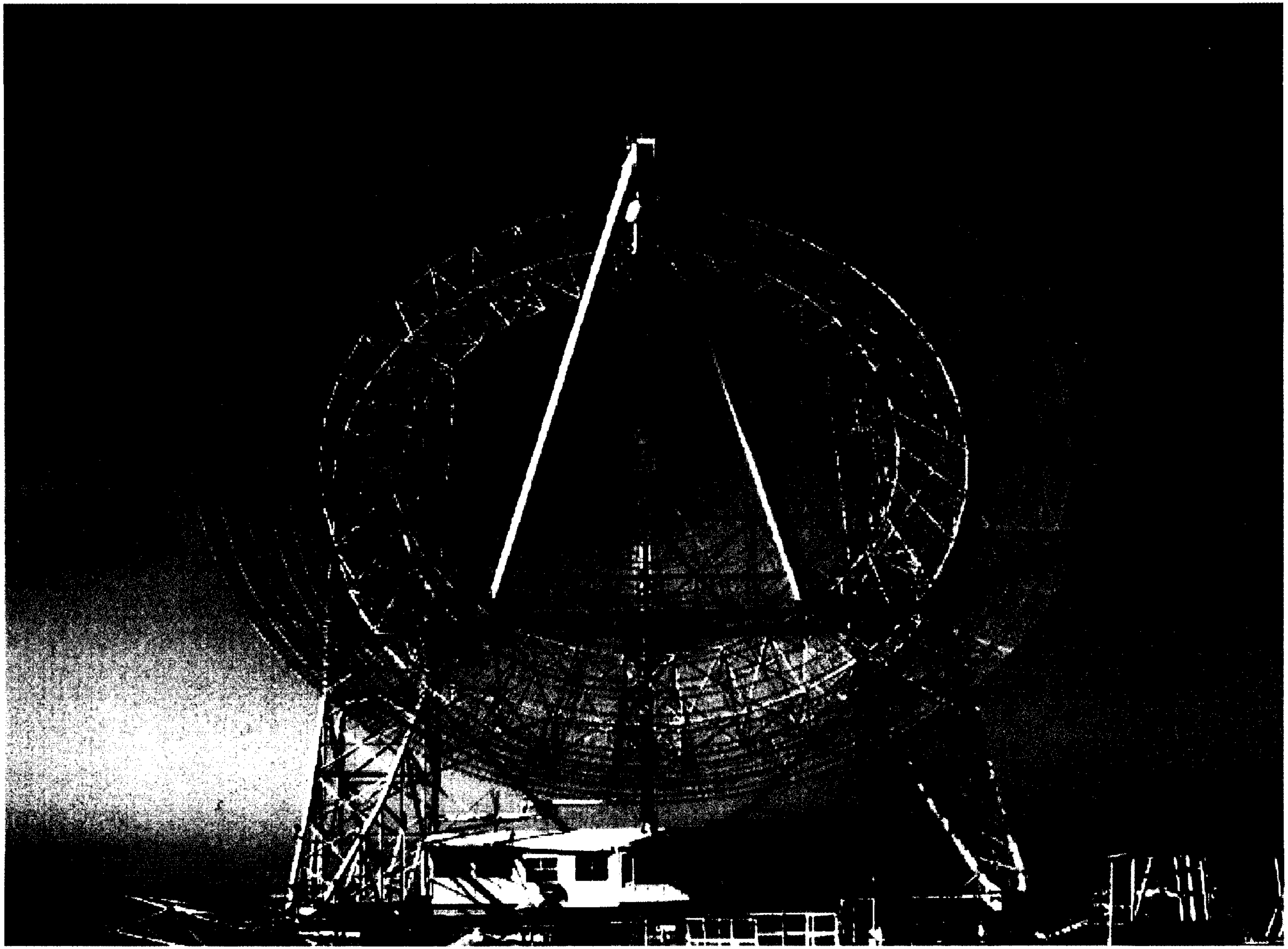


Figure 6. The SRI 46-meter Antenna. SRI International operates the Big Dish, located at Stanford University.

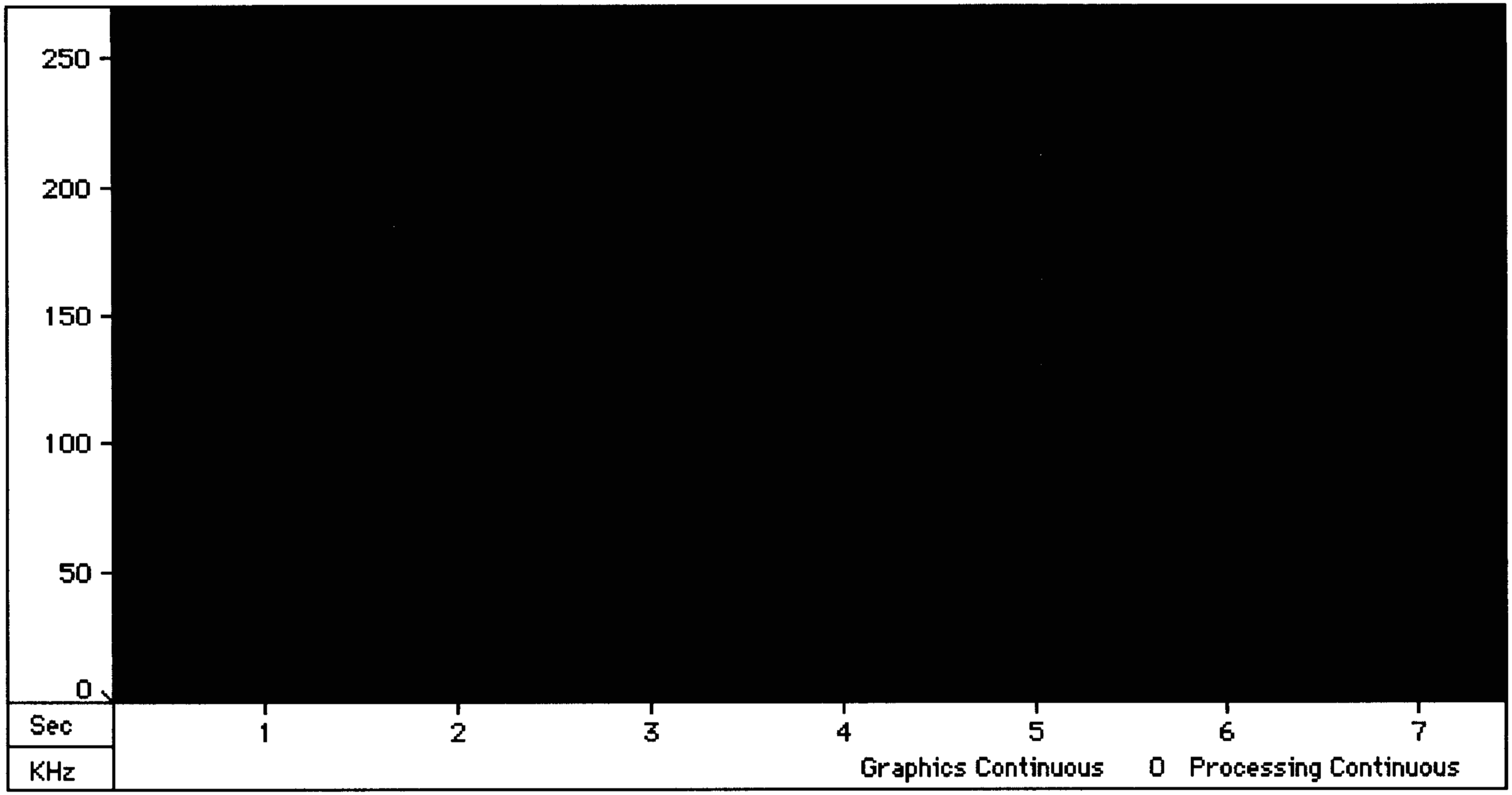


Figure 7. Waterfall Spectrum of the Mars Relay Beacon and Subcarriers for Mode 12. This waterfall spectrum was collected during the Mars Relay UHF Flight Test in November 1996. The "stitch" pattern of the subcarrier FM harmonics from the alternating BTTS every 16 seconds between RC1 and RC3 is readily apparent. Brief pulses of pure carrier (CW) are also seen, as expected.

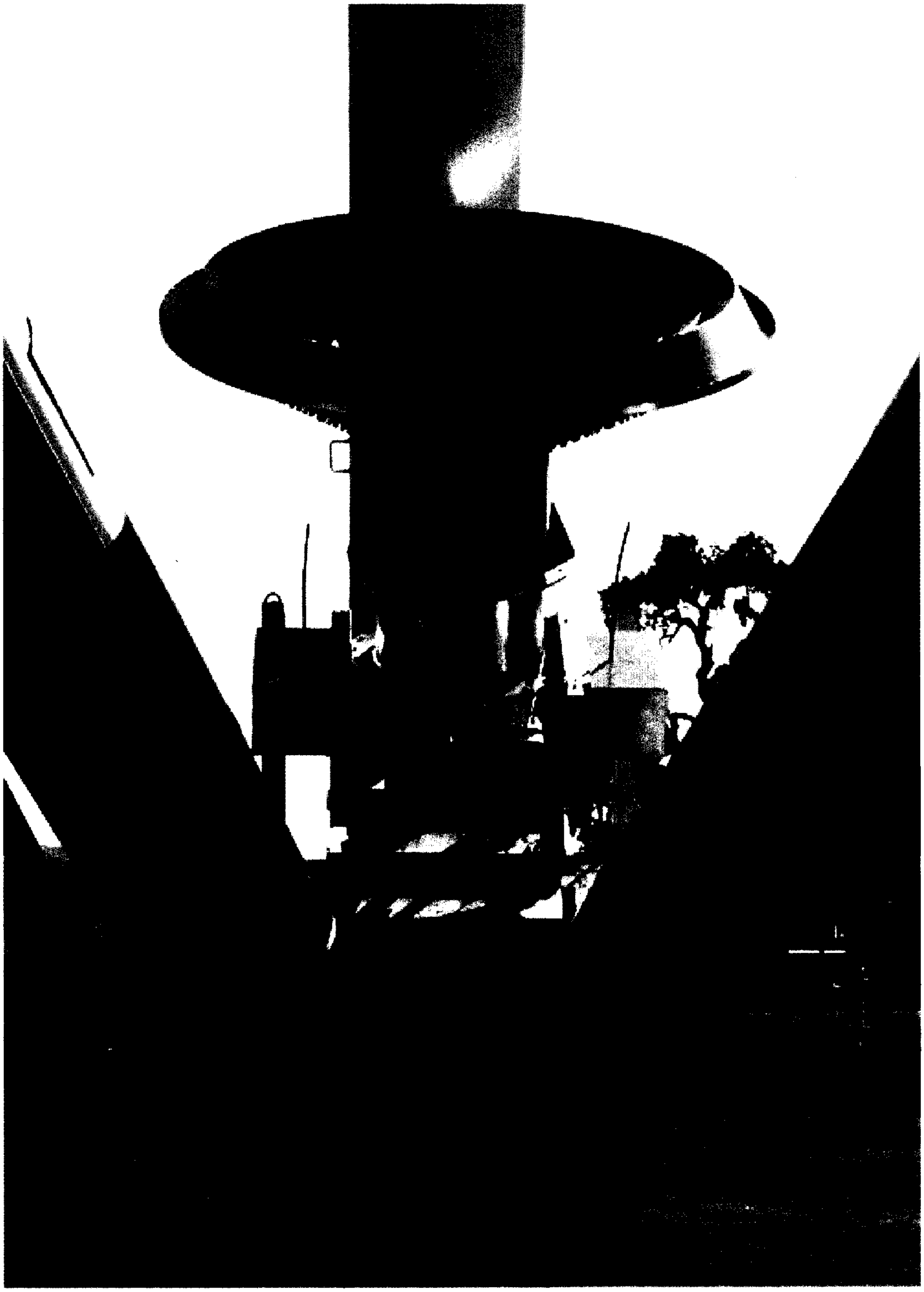


Figure 8. The "Mars" UHF Feed Horn. The corrugated feed horn and turnstile is mounted on apex of the tripod on the SRI 46-meter Antenna. Tuning stubs are visible at two ports on either side of the central feed. Low noise amplifiers and filters are mounted on the other two turnstile ports.

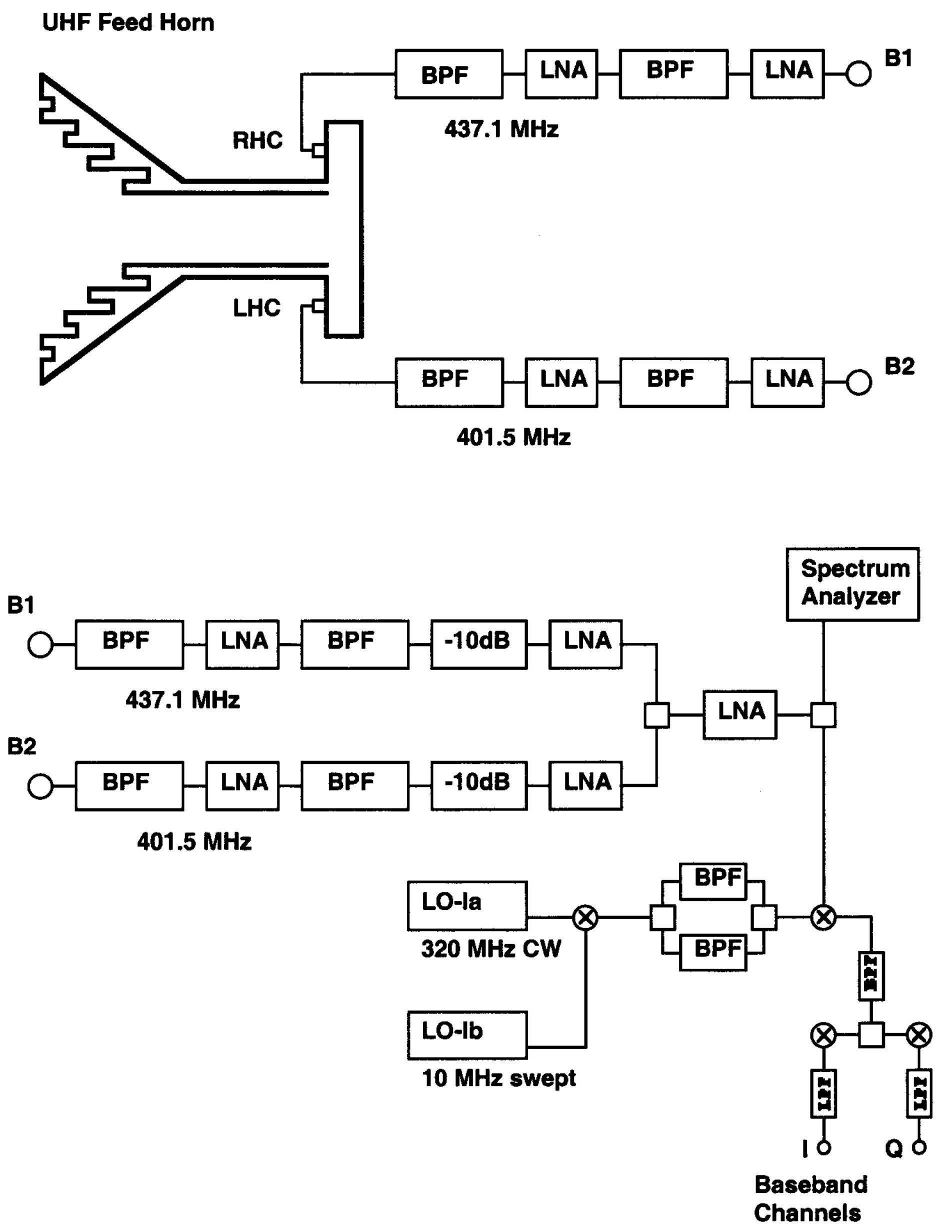


Figure 9. Block Diagram of the SRI 46-meter Antenna Receiver System. A dual channel, dual polarization UHF receiver is shown that that was used for the Mars MR observations. This receiver can select either right-hand Circular or left-hand circular polarization, for either of two UHF RF channels 437.1 MHz or 401.5 MHz. The receiver contains an RF front end, which is mounted on the feed horn at prime focus, and a downconverter section that incorporates two heterodyne stages to mix the UHF RF to baseband I and Q channels. A programmed local oscillator (LO) in the first mixing stage performs Doppler compensation and selects between the two RF channels

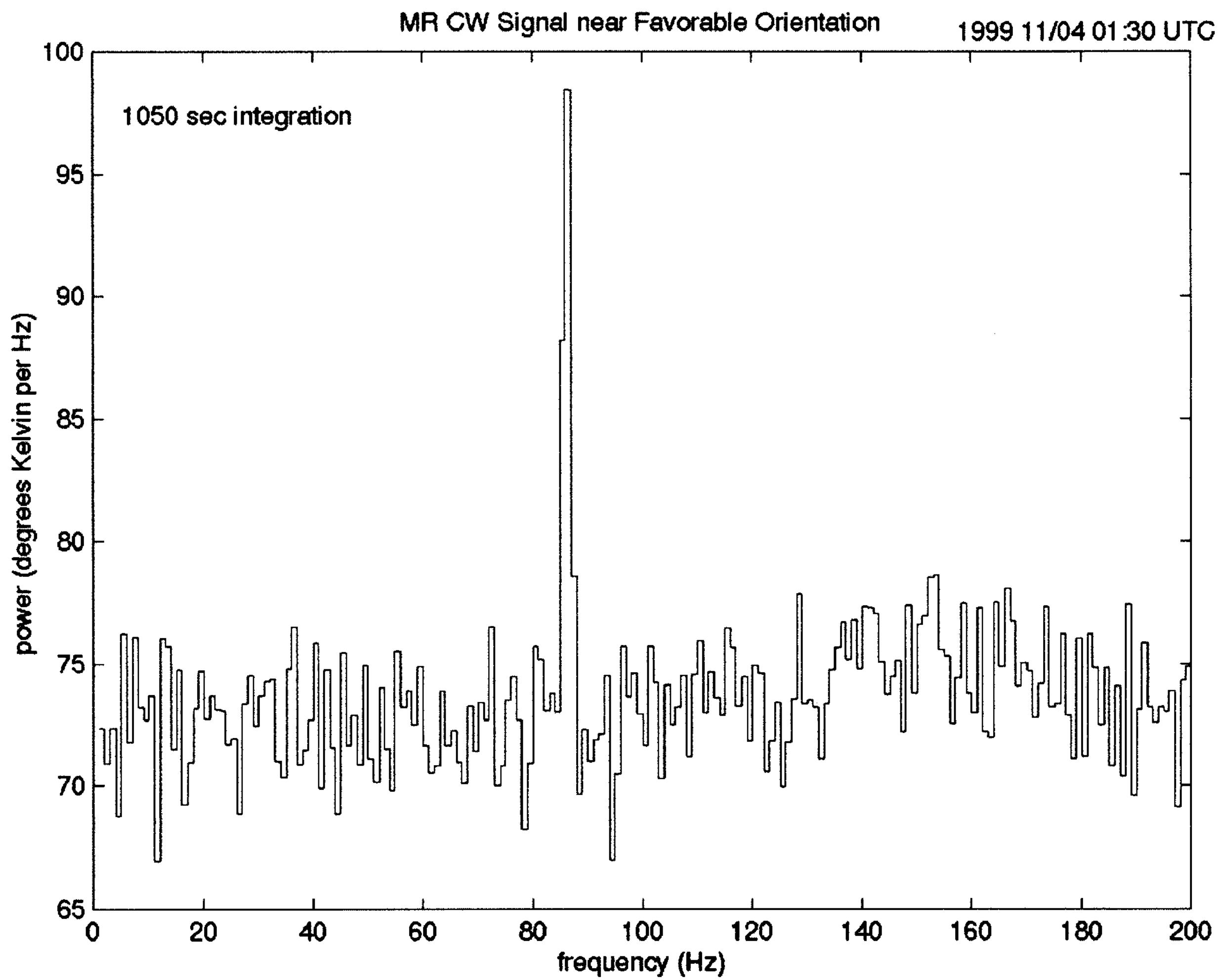


Figure 10. Spectrum of the Mars Relay CW Beacon. This spectrum resulted from the post-processing of data collected at the Big Dish on 1999-11-03 of the Mars Relay CW beacon. An inversion for incorrect Doppler compensation had to be applied in order to resolve the signal.

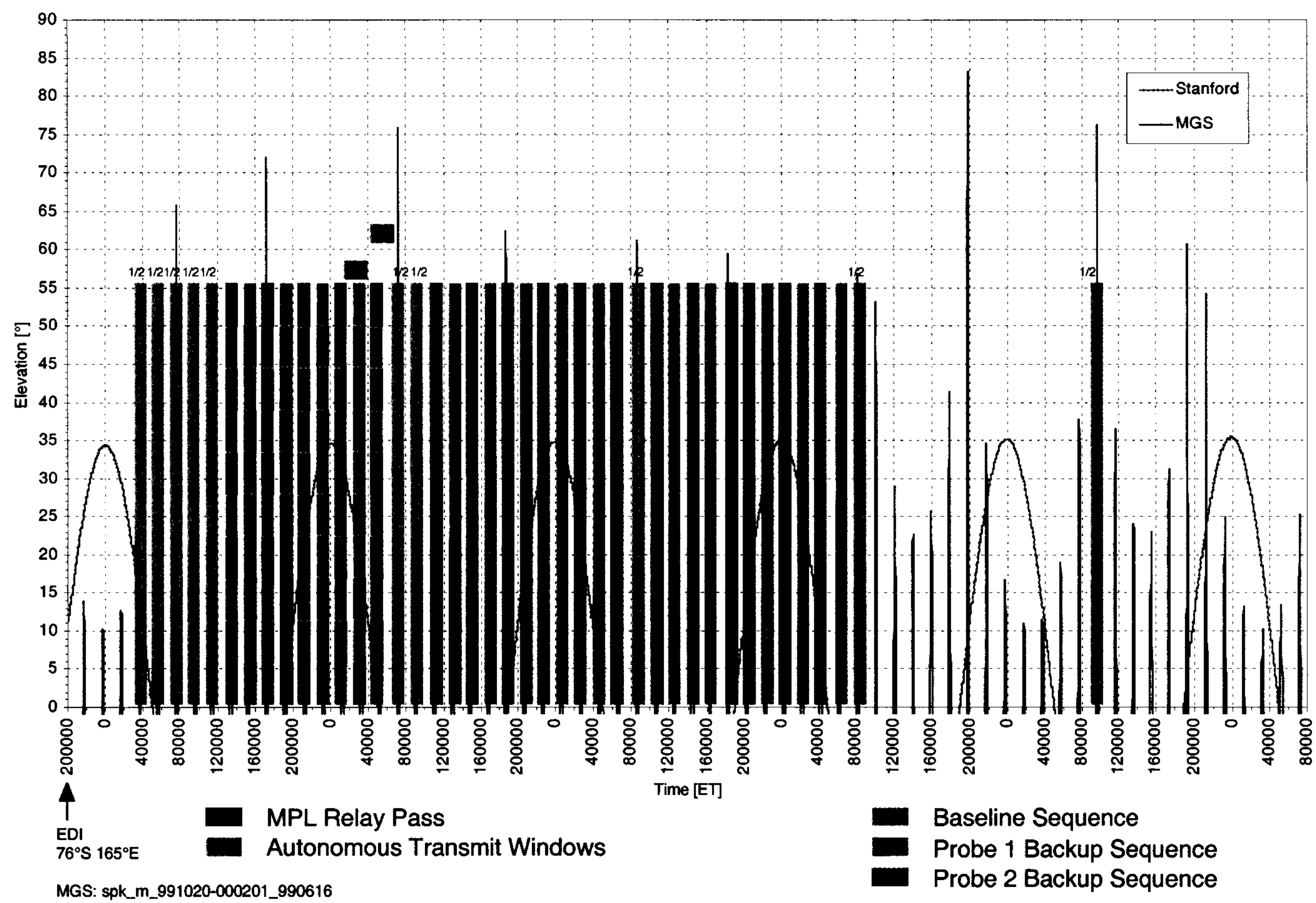


Figure 11. Mars Relay Sequencing for DS-2 Data Return. An arrangement of three concurrent active sequences on board MGS controlled the operation of the Mars Relay for data return. Each communication pass is 24 minutes in duration. Passes on Sol 0, alternate every 2.4 minute between each probe. For nominal operation by either one or both probes after landing, either backup sequence, or both, can be terminated by ground command to MGS.

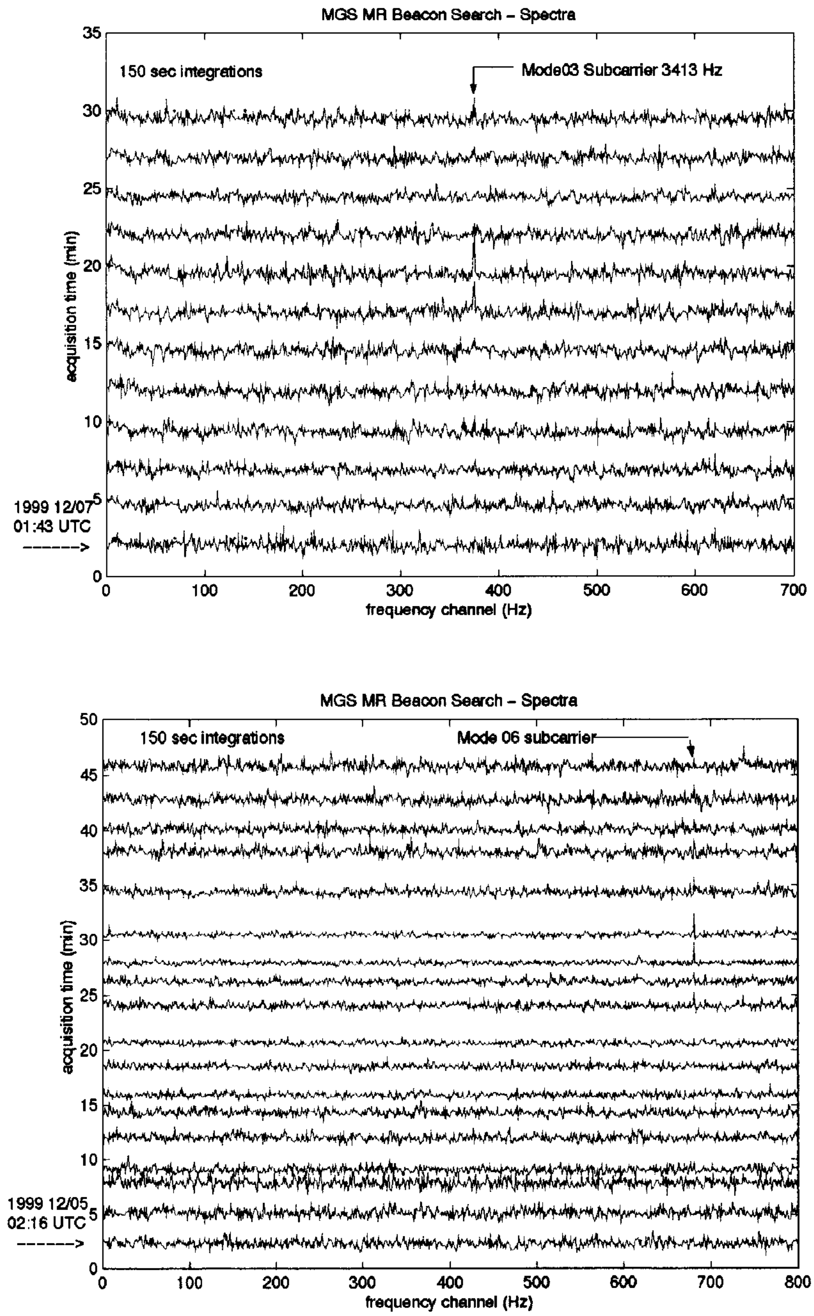


Figure 12. Spectra of Mars Relay FM subcarriers from Modes 03 (top) and 06 (bottom). The subcarrier harmonics, RC2 from Mode 03 and RC3 from Mode 06, were observed directly by the Big Dish. The signals were observed at the correct frequency and signal strength, and at the correct time in the MGS orbit.

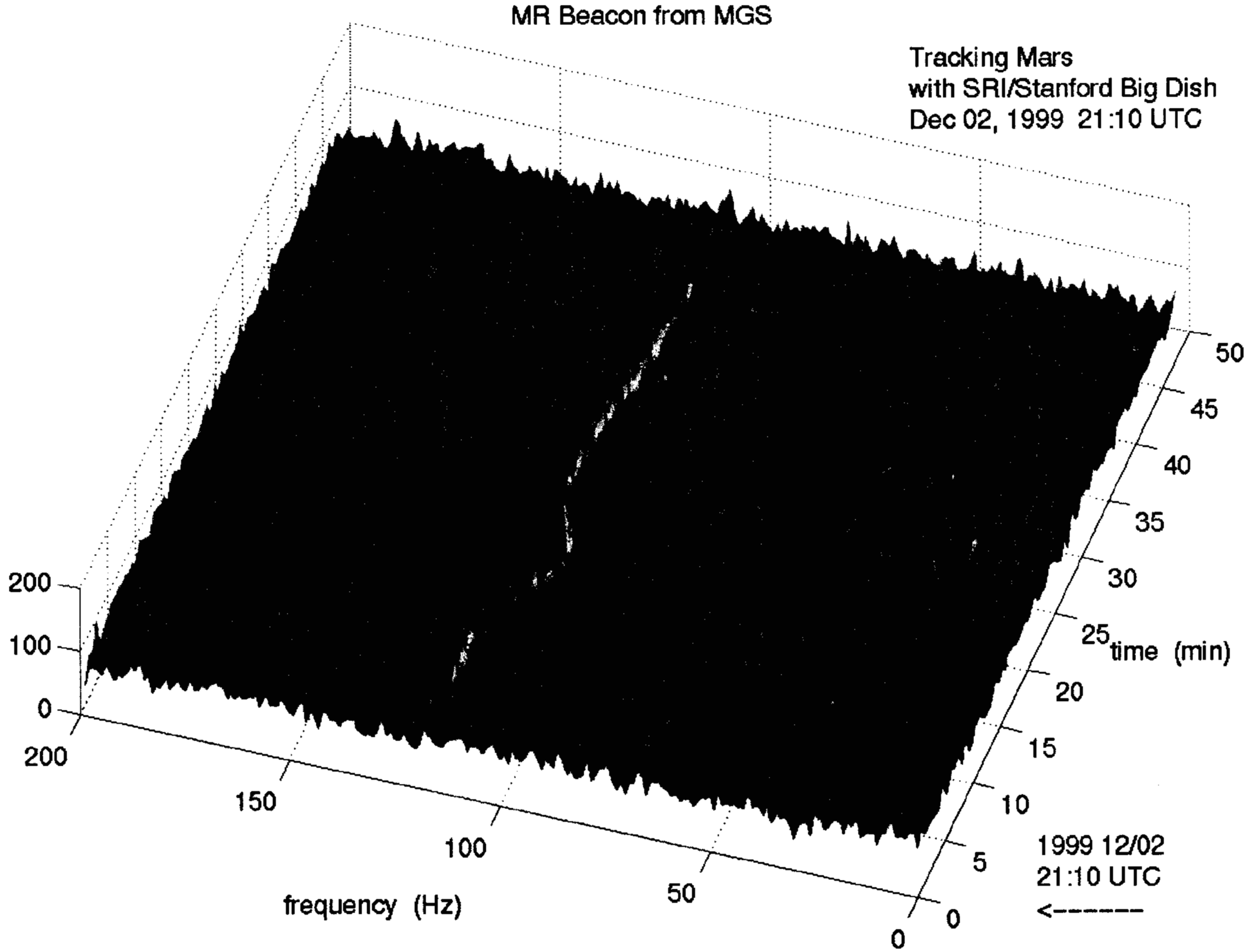


Figure 13. Time/Spectral Plot of the Mars Relay CW Signal on 1999-12-02. The MR CW beacon is seen at the expected frequency (mixed to baseband) and signal strength, and at the expected time. However, a small frequency variation is noted.

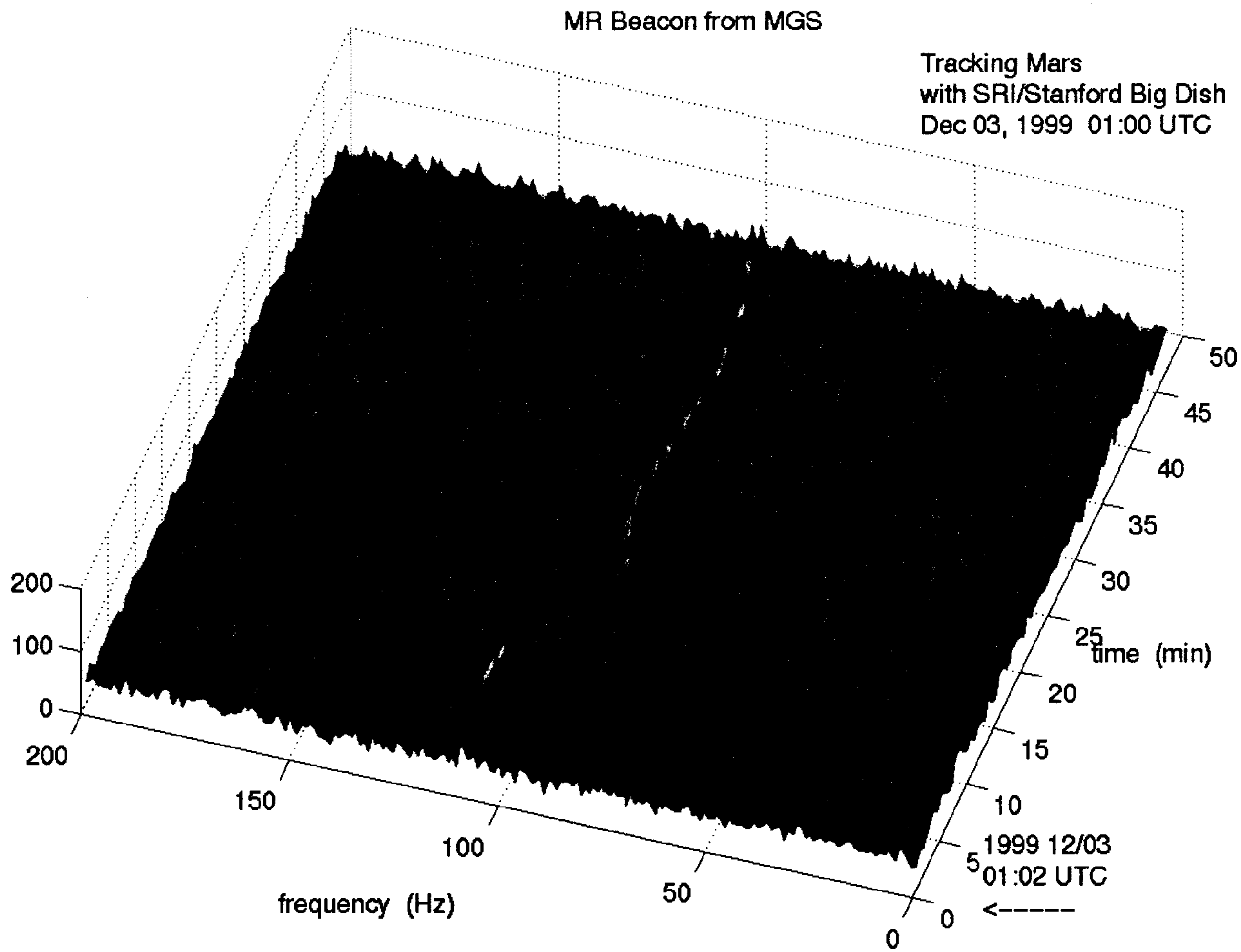


Figure 14. Time/Spectral Plot of the Mars Relay CW Signal on 1999-12-03. The MR CW beacon is seen at the expected frequency (mixed to baseband) and signal strength, and at the expected time. However, a small frequency variation is noted.

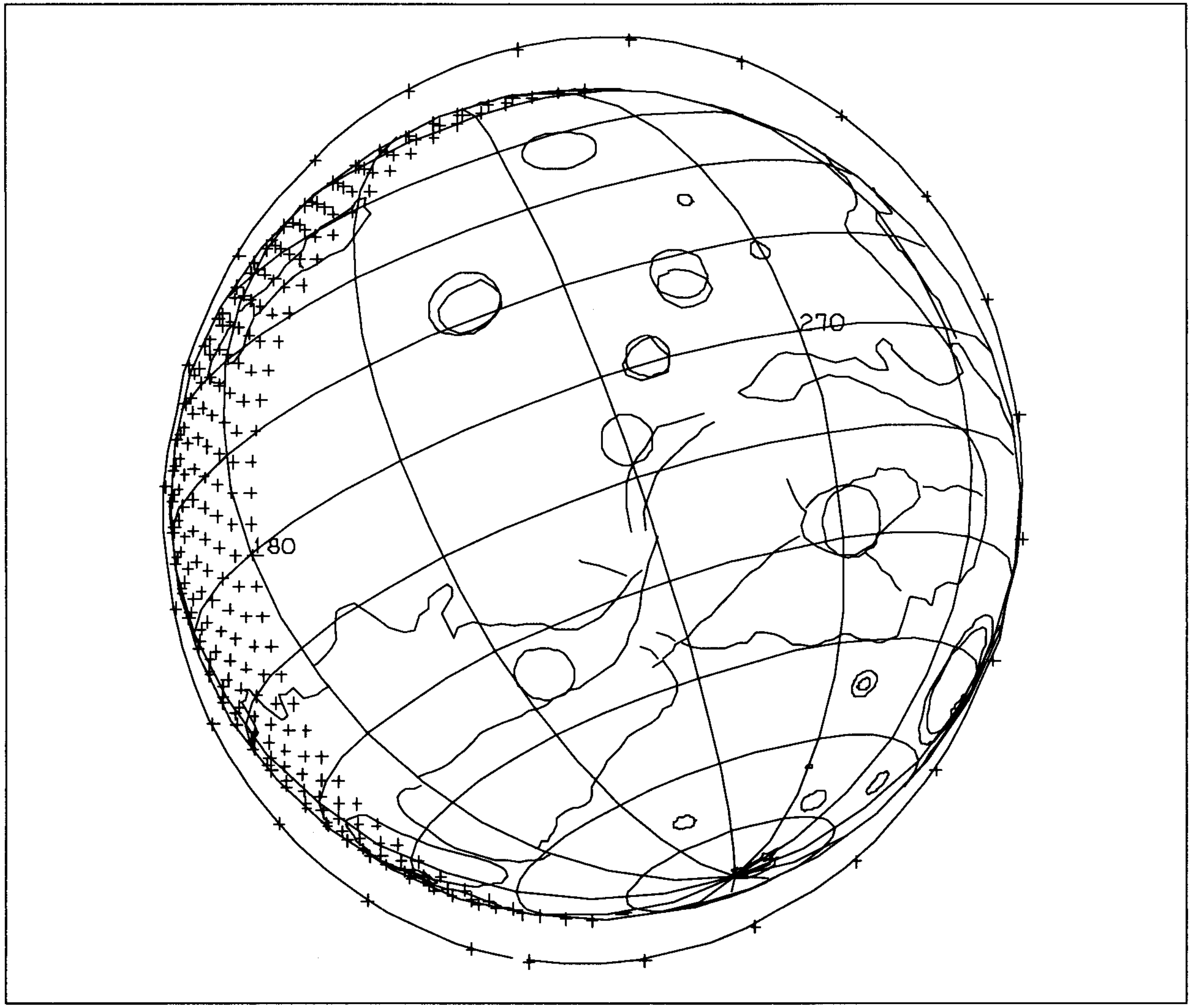


Figure 15. MGS Orbit about Mars on 1999-12-02. The plot illustrates the view from Earth of the MGS orbit about Mars. The spacecraft raypath descends through the Martian atmosphere and almost becomes occulted on the backside of the orbit.

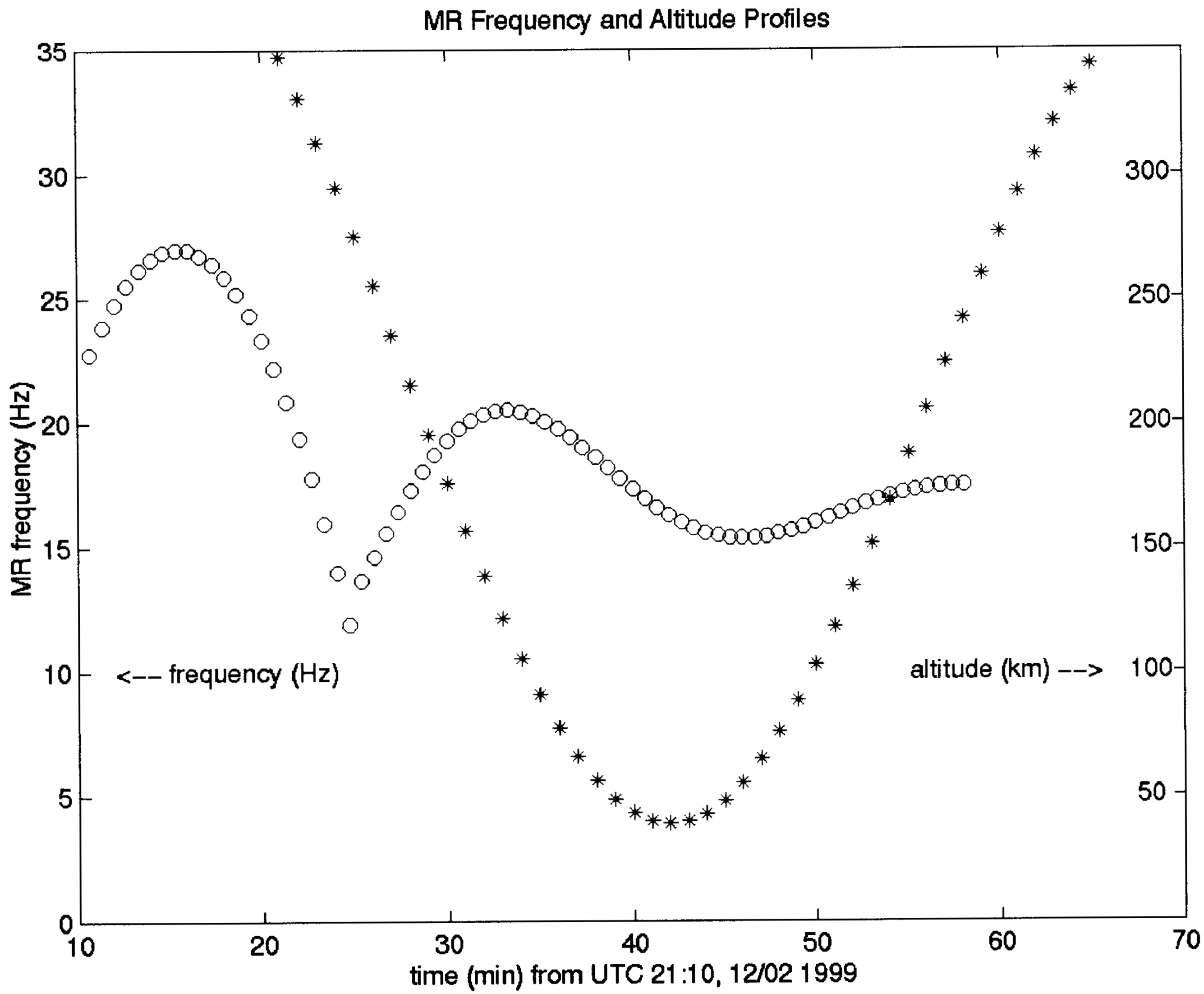


Figure 16. Frequency/Altitude Profiles of the Mars Relay CW Signal